Urban microclimate in temperate climates: a summary for practitioners

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BUILDINGS & CITIES

Urban microclimate in temperate climates: a summary for practitioners

BRIEFING NOTE

ROHINTON EMMANUEL

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ABSTRACT

A summary is presented of current knowledge and key considerations in urban climate mitigation that have a bearing on planning practice in temperate climates. Urban climate is the intended or unintended local climate consequence of planning decisions at the street, neighbourhood and even city scales. Such local climate change adds to the changing global climate, where it both interacts with as well as exacerbates the human, energy, built environment and urban consequences of climate change. Although a relatively new field of study, knowledge about urban climate has sufficiently grown in recent decades to be of practical value to decision-making in the design and planning arenas. The climatic, wellbeing and carbon impacts of urban climate change are summarised along with best practices in mitigation and their relative merits. Key action points involve mapping heat vulnerability as well as enhancing heat resilience. It is hoped this briefing note will raise awareness of the wide range of issues involved in responding to the urban climate anomaly, whether in planning new districts or infilling existing ones.

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cities; climate change; climate-sensitive design; heat stress; microclimate; thermal comfort; urban climate; urban form; urban heat island; urban planning

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1. INTRODUCTION

The dramatic growth in the scientific understanding of the microclimatic consequences of urban growth is increasingly yielding policies, programmes, protocols and planning codes to mitigate its negative consequences. The aim of this briefing note is to succinctly capture key considerations and current developments that have a bearing on planning practice. It highlights the current science findings as well as knowledge gaps, closing with key issues for the integration of urban heat resilience policy with climate change mitigation.

The urban microclimate anomaly is at its most distinctive state on clear (cloudless) and calm (little or no wind) nights (ranging from soon after sunset to just before dawn) and manifests itself in air temperature, relative humidity, wind (speed and direction) as well as precipitation in the manner described in ***Table 1***. It further impacts building energy needs, human comfort and wellbeing, as well as regional climate change.

Table 1: Manifestation and impact of the urban climate in temperate climates.

TYPE OF IMPACT	IMPACT PARAMETER	DESCRIPTION OF IMPACT
Climate	Air temperature	Increase in air temperature in relation to the surrounding countryside, with increases up to 6°C recorded in temperate climate cities—typically highest at night (Kleerekoper *et al.* 2017)
	Relative humidity	Drier conditions in cities arising from the nature and intensity of human activity as well as patterns of irrigation in open spaces (Phelan *et al.* 2015)
	Precipitation	Increased precipitation downwind of cities (in summer and the mornings) (Golroudbary *et al.* 2018). Air pollution exacerbates condensation and may increase regional precipitation (Freitag *et al.* 2018)
	Regional/global climate	Urban climate has a feedback with regional climates in highly urbanised regions of the world such as Western Europe (a slower increase in the daily maximum air temperature but a faster increase in the daily minimum temperature, leading to a smaller diurnal variation) (Daniel *et al.* 2018; Katzfey *et al.* 2020), but the relationship in other (less urbanised) regions as well as the exact mechanisms of the feedback are unclear
Wellbeing and biodiversity	Air quality	Transport as well as waste heat from buildings contribute significantly to air quality deterioration. Air pollution acts as a greenhouse gas to trap urban heat, leading to a feedback loop between temperature and air quality
	Vegetation and biodiversity	Local warming and air pollution reduce the vegetation's ability to provide ecosystem services (such as cooling) by interfering with its growth (Gunawardena *et al.* 2017). Additionally, local temperature changes affect the diversity of urban flora and fauna (enhancing the ability of invasive species to thrive as well as decreasing native species' ability to adapt)
	Human health	Risk of mortality due to heat increases by between 1% and 3% per 1°C change in high temperature (Hajat & Kosatky 2010). Societal costs are tempered by population density, the general economic health of the city and the fraction of the elderly population, and further complicated by equity and social justice issues
Carbon	Energy consumption	Building energy demand is decreased in winter (less heating) and increased in summer (more cooling) (Kolokotroni *et al.* 2010). The temporal differences in their peak occurrence may lead to greater carbon emissions depending on the electricity generation mix (Skelhorn *et al.* 2018). The configuration of buildings with respect to one another and the thermal properties of buildings and pavements will influence building energy demand in complex ways (*cf.* Futcher *et al.* 2018)
	Water (quality and quantity)	Increases in water use (*e.g.* for irrigation) as well as runoff (due to paving and roads). Sealed surfaces also reduce water availability to absorb heat, leading to temperature changes. Rise in surface temperature affects water runoff temperature as well as chemistry, leading to a loss of water quality (Phelan *et al.* 2015)
	Economic impacts	Higher cooling loads (thus, higher energy use) and productivity losses have economic consequences. This is further exacerbated by air quality deterioration

2. CAUSES

Cities tend to absorb more of the total available heat (*i.e.* solar radiation plus heat generated from human activities), thereby raising the urban air temperature. The way land is used and covered, the configuration (massing) of buildings relative to each other and in relation to streets, the thermal properties of building materials and pollution from human activities all add to the unique urban signature on local climate.

At street level, the height of buildings with respect to the width of streets (also known as the aspect ratio) and the direction of the wind with respect to the street layout determine the nature of air flow within resultant canyons. These influence both their temperature as well as their air quality. Differential heating of canyon walls (especially the windward walls) and the addition of roughness elements (such as awnings, protrusions and setbacks) in combination with an appropriate canyon aspect ratio (especially a square canyon, where the average height of buildings is equal to the width of street) could enhance street ventilation (Fellini *et al.* 2020).

The influence of urban as well as street-level parameters on local climate is dependent on the location of the city (the 'latitude effect'). At lower latitudes with high levels of solar insolation (*i.e.* the amount of energy from the sun), street-level conditions are less likely to be affected by building shading. At higher latitudes, the effect of solar insolation is highly dependent on the geometry of building forms. Street layout (*e.g.* diagonal streets *versus* a grid pattern oriented along the cardinal directions) add further complications. Urban density—whether induced by 'vertical' parameters such as the floor area ratio (FAR) or facade area as indicated by the facade-to-site ratio, or 'horizontal' density as indicated by plan area density (PAD) that indicates the extent of plot coverage—also influences the local climate (Chatzipoulka & Nikolopoulou 2018). High horizontal density would lead to stronger urban climate anomaly in winter (***Table 1***), while an increase in vertical density would result in an intense summertime urban heat island (UHI) (Salvati *et al.* 2019).

Planners and designers may be able to influence the horizontal density (the compactness of an urban arrangement) and the vertical density (the height of buildings as well as the efficiency with which the built volume is enclosed by the building envelope). These could be used to enhance local thermal comfort at street level.

Figure 1 summarises these interactions at both the street and citywide scales to highlight the planning controls that could be used to ameliorate the negative consequences of urban climate. Street geometry, built form, vegetation and the thermal properties of materials are the key levers to control urban climate at local scales. The use of these need to be context specific and wider questions relating to urban activities, land use and functions should also be considered (Jamei *et al.* 2016). Human thermal comfort depends not only on air temperature but also on other factors such as wind, solar reflectance and humidity (Heris *et al.* 2020). Thus, urban climate mitigation needs an integrated approach that addresses all local climate conditions simultaneously.

3. APPROACHES TO MITIGATION

Attempts to mitigate the negative consequences of urban climate need to consider the questions of WHAT we want to change as well as WHERE we want to achieve this. In terms of the 'what' question, the goals of mitigation options can be grouped into three:

- *Climate improvement*: temperature control to manage heatwaves and mitigate overheating, reduce interference with humidity and precipitation.
- *Health and wellbeing*: thermal comfort and air quality enhancement; health, productivity and comfort; and improvements to biodiversity.
- *Carbon management*: efficiency enhancement in energy and water use.

Tools and approaches to achieve these at scale are three-dimensional urban form, nature-based solutions (NbS) and the manipulation of the surface properties of buildings.

In terms of urban form, volumetric compactness (horizontal density), aspect ratio and form factor (vertical density), plot surface, openness to sky (as given by the sky view factor and distance to the nearest wall), and land cover types (especially hard surfaces that act as heat sources or soft surfaces that act as heat sinks) are all important for mitigating the negative consequences of urban climate (Giridharan & Emmanuel 2018). The presence of open spaces, the shape of building

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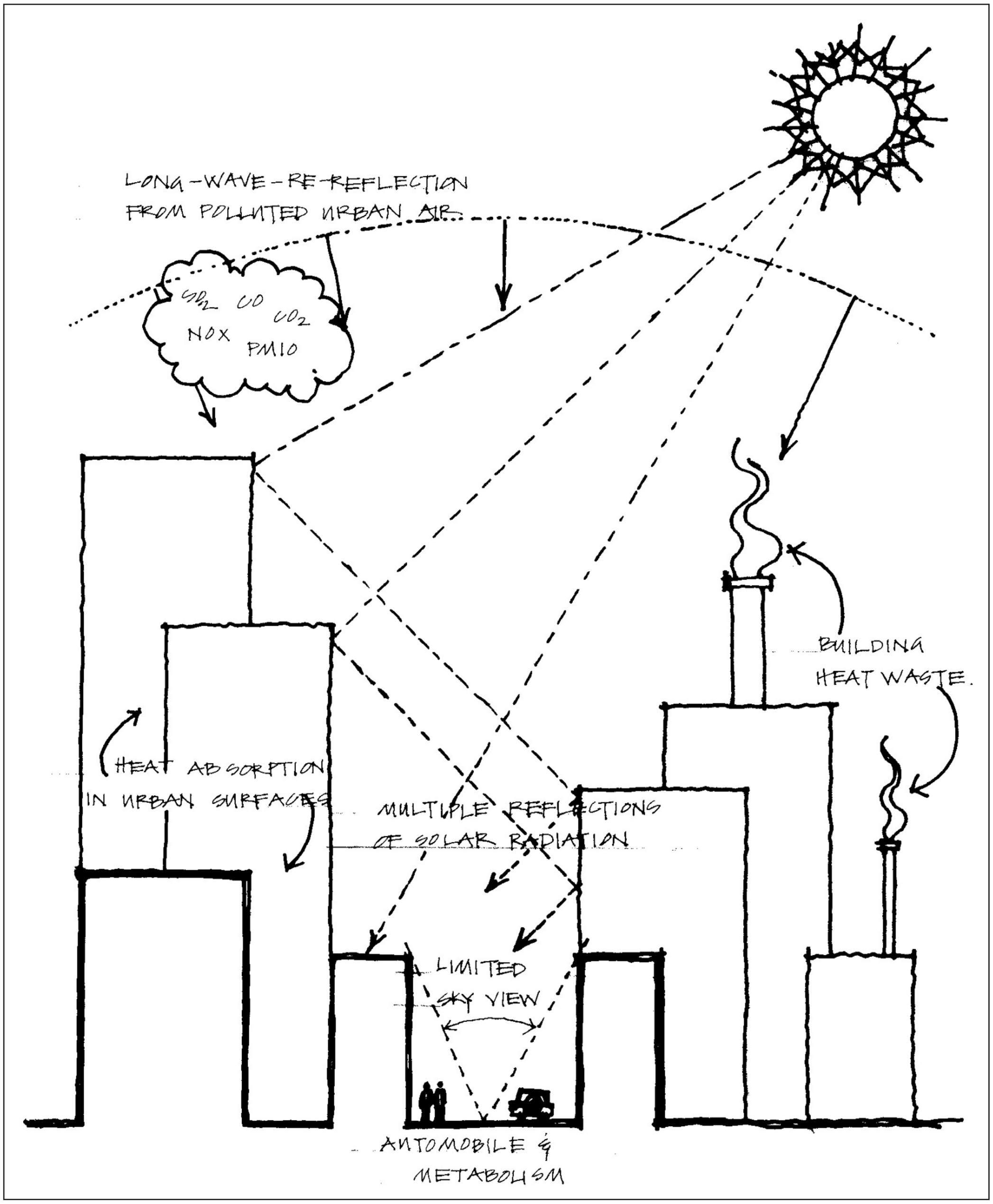

Figure 1: Summary view of the factors affecting the urban climate.

Source: Emmanuel (2005).

envelopes and the symmetry of the street further add to local-level (at the street scale) thermal comfort variations during the day (Guo *et al.* 2019).

Solar geometry dictates the prioritisation of streets and facades. East–west canyons receive more direct sun than north–south canyons and therefore solar radiation falling on eastern and western facades has the most impact on the microclimate. Its impact on north and south facades makes negligible contributions to pedestrian thermal comfort (Taleghani *et al.* 2021).

The NbS can also be applied to urban climate mitigation, including green (vegetation) and blue (water) infrastructures. The evapotranspiration-based cooling influence of both green and blue space is critical to the lower atmosphere in cities (*i.e.* the space from ground up to the average height of roofs—the 'urban canopy layer'). The magnitude and spread of cooling by NbS depends on the size, spread, distribution and geometry of such solutions. Solitary large parks offer minimal cooling across large areas (Gunawardena *et al.* 2017), whereas a more distributed provision of green spaces spreads the cooling benefit more widely. However, city-scale cooling is mainly derived from the increased surface roughness of green space (*i.e.* improved convection efficiency) rather than evaporation (Gunawardena *et al.* 2017). Blue space cooling during the day can be substantial, but there is a nocturnal warming penalty. When both green and blue spaces are employed together, they can offer many synergistic ecosystem benefits, including cooling (Gunawardena *et al.* 2017).

For thermal comfort in the streets and neighbourhoods (as opposed to mere air temperature at the street level or across the city as a whole), trees in combination with buildings, grass verges against paved surfaces, and aligning the streets along predominant wind directions can all help to mitigate thermal discomfort in summer (Kleerekoper *et al.* 2017) without a significant wintertime penalty. In terms of 'efficient' positioning of trees, the north-east side of a north-west to south-east street or the north side of an east–west canyon is more useful while their positioning in north–south or north-east to south-west street canyons is more flexible (Chatzidimitriou & Yannas 2017).

Building envelopes provide the third set of urban climate mitigation possibilities. The choice of materials depends on street orientation (Taleghani *et al.* 2021). A high albedo (*i.e.* high solar reflectance) enables heat to be quickly radiated back into the atmosphere (Hoverter 2012). High-albedo roofs are widely used in the US (so-called 'cool roofs'), where a combination of building codes, grant programmes and utility rebates are deployed to reduce both the building energy needs as well as urban air temperature. However, there are uncertainties related to the value for money of the high-albedo approach at city scales as opposed to energy savings to individual buildings (Pomerantz 2018).

The final question to be answered in urban climate mitigation is WHERE interventions should be attempted. The scale of interventions could either be macro (city wide) or micro (neighbourhoods to single street blocks). The former is more beneficial in terms of climate improvement and carbon management, whereas the latter has more immediate health and wellbeing benefits. All three approaches (urban form, NbS and building surfaces) are amenable to both scales.

3.1. COMPARATIVE BENEFITS OF MITIGATION APPROACHES

Both urban form and NbS could provide shading that leads to improved thermal comfort as well as improved ventilation. Both the shading effects as well as the influence of air ventilation are useful to reduce surface temperature (Peng *et al.* 2017). While urban form has the ability to promote/hinder shading and ventilation, trees provide additional 'non-climate' benefits (such as CO_2 sequestration, oxygen generation, pollutant removal, and recreational and amenity benefits) (Cheung & Jim 2018). Their location and spacing with respect to street geometry are important street design considerations.

In terms of NbS *versus* surface thermal properties, a city-wide increase of albedo would not be as effective at lowering the average ambient temperature when compared with green (vegetated) surfaces (Santamouris 2014). In sunny climates, reflective roofs present an important advantage, while in moderate and cold climates vegetative roofs present higher benefits. Additionally, weatherisation is a serious problem for reflective surfaces. High levels of reflective surfaces in urban areas (*i.e.* albedo > 0.3) are impractical (maintenance difficulties due to air pollution and precipitation as well as excessive glare). The installation of reflective roofs on high-rise buildings is unlikely to make much impact on urban climate. A practical level of albedo improvement (up to 0.3) with a moderate level of green cover (up to 20% of the urban surface) has the greatest potential to improve the urban microclimate (Yuan *et al.* 2017).

4. URBAN CLIMATE MITIGATION IN PRACTICE

Practical approaches to mitigate the negative consequences of urban climate are emerging around the world in terms of mapping and analytical tools as well as planning codes (***Table 2***).

Applying current knowledge about urban climate to urban planning requires the accurate characterisation of land use/land cover and the functions of urban neighbourhoods. Typically, planning considers urban space in terms of discrete sets of urban form or land-use-based zoning, or a combination thereof. However, amelioration of urban climate calls for an integrated, goal-oriented approach (climate improvement, health and wellbeing, or carbon management) to better describe the urban form and to deal with the intrinsic complexity of urban spaces (Vanderhaegen & Canters 2017). The recently introduced Local Climate Zone (LCZ) approach (Stewart & Oke 2012) provides a useful method to combine both the form and function of urban spaces from a local climate point of view.

APPROACH	DESCRIPTION	INTENDED USERS	POINT OF APPLICATION
Urban climate mapping	Urban climate mappings (UCMaps) consist of a UC-AnMap, which analyses climatic, geographical and planning information in map form, and a UC-ReMap, which develops planning instructions from an urban climatic point of view (see Ren *et al.* 2011 for a review). Useful technical standards exist for UCMap (VDI 1997)	Urban planners and urban designers	Masterplan, zoning plan and local development plan
Shading analysis	Optimising street canyon geometry to enhance the thermal comfort in public places offers several approaches to enhance shading. These include shadow-casting by buildings on public places and the 'urban cool umbrella' (*https://www.castrucciarchitect.com/urban-cool-umbrella*) that uses street furniture to enhance shading in public places	Urban designers, building designers and building services engineers	Street design and preliminary planning approval for buildings
Ventilation analysis	Following from the Severe Affective Respiratory Syndrome (SARS) epidemic in 2003, the Hong Kong government promulgated air ventilation assessment (AVA) regulations (Hong Kong Government 2006) to monitor the air flow effects of buildings. AVA uses the velocity ratio as an indicator of wind availability	Urban planners and public health officials	Masterplan, urban regeneration and neighbourhood development plan
Planning codes as toolkits to manage urban heat	Several heat island-mitigation toolkits and codes (including mandates and incentives) exist in the US to facilitate decision-making at local government levels. These include the 'cool roofs' programme (enhancing roof albedo); 'green roof' (intensive and extensive roof green cover); 'cool pavements' (similar to cool roofs, but for pavements) and urban forestry regulations (see Hoverter 2012 for a review)	Urban planners, building designers, building services engineers and public health officials	Streetscape design and building design

Table 2: Practical tools for urban climate mitigation.

5. ACTION POINTS

Planning approaches to urban climate mitigation should be seen as part of the wider, climate change vulnerability actions. The mapping of heat vulnerability provides a way to couple surface UHI measures with socioeconomic indicators of vulnerability. ***Figure 2*** provides a framework to tackle heat vulnerability and bring adaptation responses to global climate change together with urban climate-mitigation measures to reduce risks at both scales simultaneously.

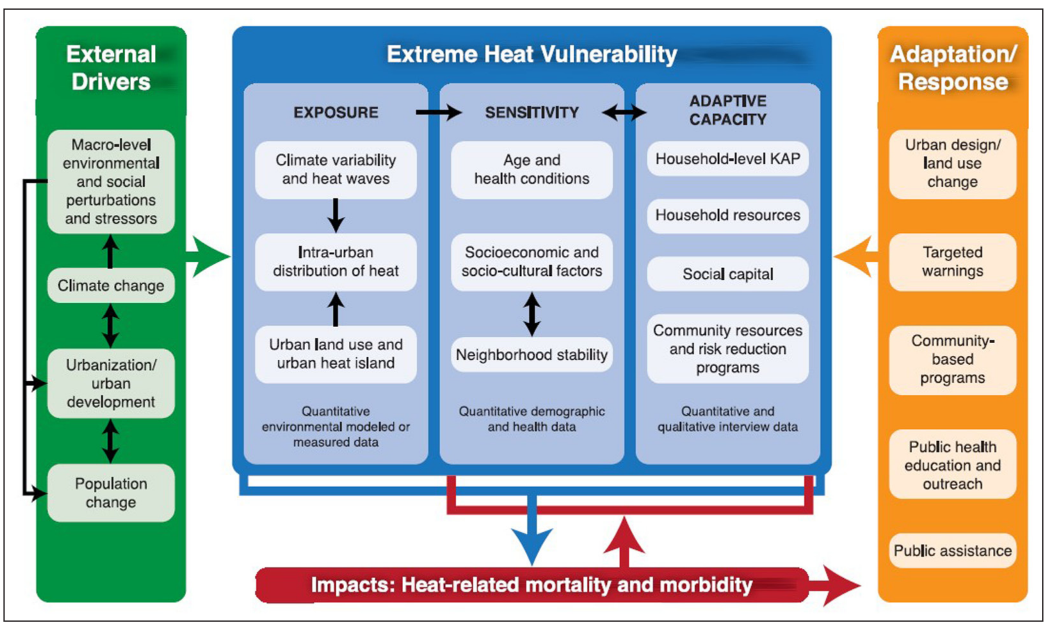

Figure 2: Heat vulnerability framework.

Source: Wilhelmi & Hayden (2010).

Having mapped the heat vulnerability, planning action could focus on enhancing heat resilience. Heat resilience in this context refers to urban planning, building design, public health and infrastructure provision to increase the quantity and quality of coping strategies. ***Table 3*** provides a policy framework indicating four areas where action is needed for such heat resilience.

POLICY AREAS	ACTIONS
Public health	Hotspot mapping; heat-related workload scheduling; and heat-related health and safety management
Building regulations	Heat stress-resistant building design guidelines; building morphology and form controls; control of building surfaces/material properties; financial incentives; include heat stress resistance in building energy certification; demonstration buildings
Planning actions	Cool refuges/public places for adaptation; heat mapping as part of an urban planning framework; urban climate mapping; ventilation and shadow assessment; open space/nature-based solutions (NbS) as part of the planning framework, inclusion of future climate scenarios for current regulations and practices
Infrastructure and services	Enhance infrastructure demand monitoring and modelling to account for heat stress; adopt public transport infrastructure to heat stress; review water and electricity infrastructure to manage heat-related demand

Table 3: Action areas for an urban heat resilience policy.

Source: Adapted from Hatvani-Kovacs *et al.* (2018) and based on discussions in this Briefing Note.

Global climate change will impose additional pressures on urban climates. This is likely to result in an increasing frequency and length of warm events, significantly influencing how the local climate is experienced by urban dwellers. The 'southward shift' of climate in cities provides an easy way to understand the urban climate of the future. Cities in the Northern Hemisphere, especially in Europe, follow a north-to-south transect at about 3–13 km/year. This average southward velocity is expected to double throughout the 21st century (Rohat *et al.* 2018). It is therefore possible for 'northern' cities to learn planning and urban design lessons from cities further south, including the benefits of shading, more compact development and more explicit use of NbS.

Such lessons should focus on climate-sensitive urban design, integrated land use and urban densification. Using the action areas highlighted in ***Table 3***, planning authorities could establish a set of context-specific principles in terms of the three 'goals' of urban climate mitigation (see 'Approaches to mitigation') at different levels of granularity (site, street, neighbourhood, city).

Not all lessons from warm places are positive. Special mention must be made of the urban densification pressures (both horizontal and vertical density) that can exacerbate the urban microclimate anomaly. The heat vulnerability framework in ***Figure 2*** shows a way to balance the drivers and responses to enhance resilience to heat and therefore urban liveability in the face of climate change.

GLOSSARY

Albedo	Fraction of solar radiation reflected from a surface
Aspect ratio	Ratio between the width of a street and the average height of buildings that abut it
AVA	Air ventilation assessment
Cool roof	A high-albedo roof
FAR	Floor area ratio
Form factor	Measure of vertical density
NbS	Nature-based solutions
PAD	Plan area density
SARS	Severe Affective Respiratory Syndrome
UC-AnMap	Urban climate analysis map
UC-ReMap	Urban climate recommendation map
UHI	Urban heat island
Urban canopy layer	Space from the ground up to the average height of roofs
Urban cool umbrella	Shadow-casting by buildings on public places
Volumetric compactness	Horizontal density

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COMPETING INTERESTS

The author has no competing interests to declare.

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